Water Resources Variability in Africa during the XXth Century (Proceedings of the Abidjan'98 Conference held at Abidjan, Côte d'Ivoire, November 1998). IAHS Publ. no. 252, 1998.

Exploring climatic impacts on water resources in west Niger, Africa

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Abstract Drought persisting in the Sahel for more than 25 years, impacting both surface and subsurface water resources, raises the question whether the hydrological impacts are proportional, dampened, or amplified in response to the climatic change manifested by the drought experienced since 1970. A physically-based distributed model, *r.water.fea*, applied to a 2.48 km^2 endoreic drainage basin, typical of the Niamey area of West Niger, is used to evaluate the sensitivity of the hydrological system to such climatic extremes under four reduced-rainfall scenarios. Scenarios are built by elimination of various subsets of recorded storm events from the four monitored seasons 1992–1995. The hydrological response varies from no decrease to nearly a 30% decrease depending on the storm selection criteria. These results emphasize the variability of the hydrological response to regional climatic changes and the importance of a detailed characterization of the hydrological process transforming rainfall into runoff at the basin-event scale.

INTRODUCTION

Prospects of reduced water supply, crop yield, and food production have prompted the consideration of the vulnerability of the local hydrological balance to global climatic changes. A growing societal demand is put on hydrologists to predict regional impacts on the water resources of the most exposed and vulnerable areas, such as the Sahel. This populated, semiarid region has been facing a severe drought for more than 25 years, and may well continue to experience such rainfall deficits. Compared to climate change, little attention has been paid to how the hydrological cycle responds to climatic change. Coupling a general circulation model with a hydrological model for forecasts of climate change impacts on water resources is envisioned. Hence, a project is under way, with the French Programme National de Recherche en Hydrologie (PNRH) to use spatially and temporally disaggregated rainfall fields from the atmospheric general circulation model developed by Laboratoire de Météorologie Dynamique (LMD), Paris, as input to a spatially-distributed hydrological model. The study area is within the square degree (2°–3°E, 13°–14°N) of the Hydrologic and Atmospheric Pilot EXperiment (HAPEX-Sahel) located near Niamey, Niger. The work presented herein addresses the sensitivity and range of possible hydrological responses to climatic change for a small basin representative of rainfall–runoff in this region of the Sahel.

Climatology of the study site

Large-scale atmospheric circulation over the region of the Sahel results in a positive gradient of annual rainfall from north to south of 1 mm km^{-1} in the vicinity of Niamey, Niger. Penetration of moisture from the Gulf of Guinea initiates the rainy season where 80% falls between the period July–September (Lamb & Peppler, 1991). As we move to the mesoscale in the Sahel, annual rainfall is the composite of convective storms of three main types identified by Desbois *et al.* (1988): local convective systems, moving organized convective systems, and squall lines (lignes de grains) which move in the direction of the tropical easterly jet. Embedded within these north–south oriented squall lines are convective cells and complexes which are responsible for delivery of rainfall in any particular catchment. As we move from the regional scale, where annual rainfall gradients are well identified, to the mesoscale, the spatial and temporal variability of rainfall patterns is more pronounced. At the catchment or point scale, the annual rainfall depends largely on the chance of a storm passing over a particular location due to the granularity of the rainfall fields at this scale. Thus, a particular catchment may experience a hydrological extreme of drought or flood that is in opposition to regional climatological conditions.

Drought as manifested in the Sahel is a reduction of rainfall. How this reduction takes place has prime importance to the concomitant evolution of runoff. Several researchers have analysed the rainfall climatology of the Sahel between 1950 and 1990, and compared the periods before and after 1970. The conclusion is shared that a dominant factor in the rainfall reduction of about 30% has been a decrease of the number of events observed during the rainy season, particularly during the most intense period of July–August (Lebel & Le Barbé, 1997; Lebel *et al.*, 1997). Le Barbé & Lebel (1997) suggest that the rainy season length and mean event rainfall depth remained relatively constant, and attribute 90% of the annual rainfall reduction to the decrease in the *mean number* of events in July and August. This indicates that a sparser distribution of events during the rainy season has been acting as the primary source of rainfall shortage in the post-1970 Sahelian drought. The impact of this drought on the hydrological response of a small endoreic basin located in the Sahel is the subject of this research.

Hydrology of the study site

The hydrological system of the 1500 km² SSZ region in the HAPEX-Sahel research area (SSZ: SuperSites Zone, a composite of the West Central and East Central Super Site, see Goutorbe *et al.*, 1994) consists of a mosaic of small endoreic catchments collecting into pools formed on plateaux and sand-blocked former river channels. Water is lost to shallow infiltration and subsequent evaporation from surface areas and ravines that convey the runoff. Water remaining in the pools infiltrates and recharges the regional aquifer in the vicinity of the pools. A comprehensive pool survey was carried out by Desconnets (1994) deriving a pool typology. The hydrology of the endoreic system of basins and aquifer characteristics is described by Desconnets *et al.* (1997). Desconnets *et al.* (1996) present a GIS and model system used to manage the spatial data necessary for hydrological simulations.

Despite the severe drought in this area, which is typical of the entire Sahel, the regional water table has shown a continuous rise over several decades within the SSZ. Though paradoxical during a drought, this is interpreted as a consequence of anthropomorphic transformation of natural land into cropland with higher runoff coefficients (Leduc & Loireau, 1997). Indeed, soil degradation and crusting induced by cultivation are considered to highly increase runoff to the pools, and hence groundwater recharge.

Considering the hydrography and toposequence controlling the runoff processes, pool level recording is the only easy way to observe runoff fluxes at the catchment scale in this area. Pool and aquifer water make up the only available water resources for the local population. Hence, within the SSZ, runoff from the endoreic catchments into the pools is the bulk source of water resource renewal in this region.

METHODOLOGY

The objective of the work presented here is to obtain an idea of the possible magnitude of water resource losses through decreased annual and interannual runoff in case of future rainfall reduction. More precisely, under the hypothesis of unchanged environment (e.g. land-use changes), the purpose is to assess the sensitivity of cumulated runoff to a large range of climatic scenarios, and to produce upper and lower bounds for possible runoff reduction relative to rainfall reduction, under these scenarios. The Wankama catchment, considered to be representative of the hydrology in the SSZ region, is used for this purpose. The geographic location of the SSZ and Wankama study site located within Niger in West Africa is shown in Fig. 1. The 1992–1995 observation period is taken to represent a reference situation from which rainfall reduction scenarios may be derived.

Catchment characteristics

The topographic sequence of features controlling runoff is typified by relatively impervious plateaux with marginal contributions of runoff over the edge to sand escarpments incised by ravines which collect runoff before discharging to a mid-slope spreading zone or sand clogged river channel (kori). Upper reaches of the ravines and the spreading zone are known to be highly pervious permitting significant runoff losses. Pools (mares) form, in some cases midslope between plateaux and valley bottoms, but generally in valley bottoms providing sources of water. Infiltrated water from ravines is largely lost to subsequent evapotranspiration; whereas, percolating water below the pools may reach the ground water table providing recharge. The Wankama catchment has average slopes on the order of 2% with steep slopes adjacent to the plateau edge. Vegetative cover is sparse with some

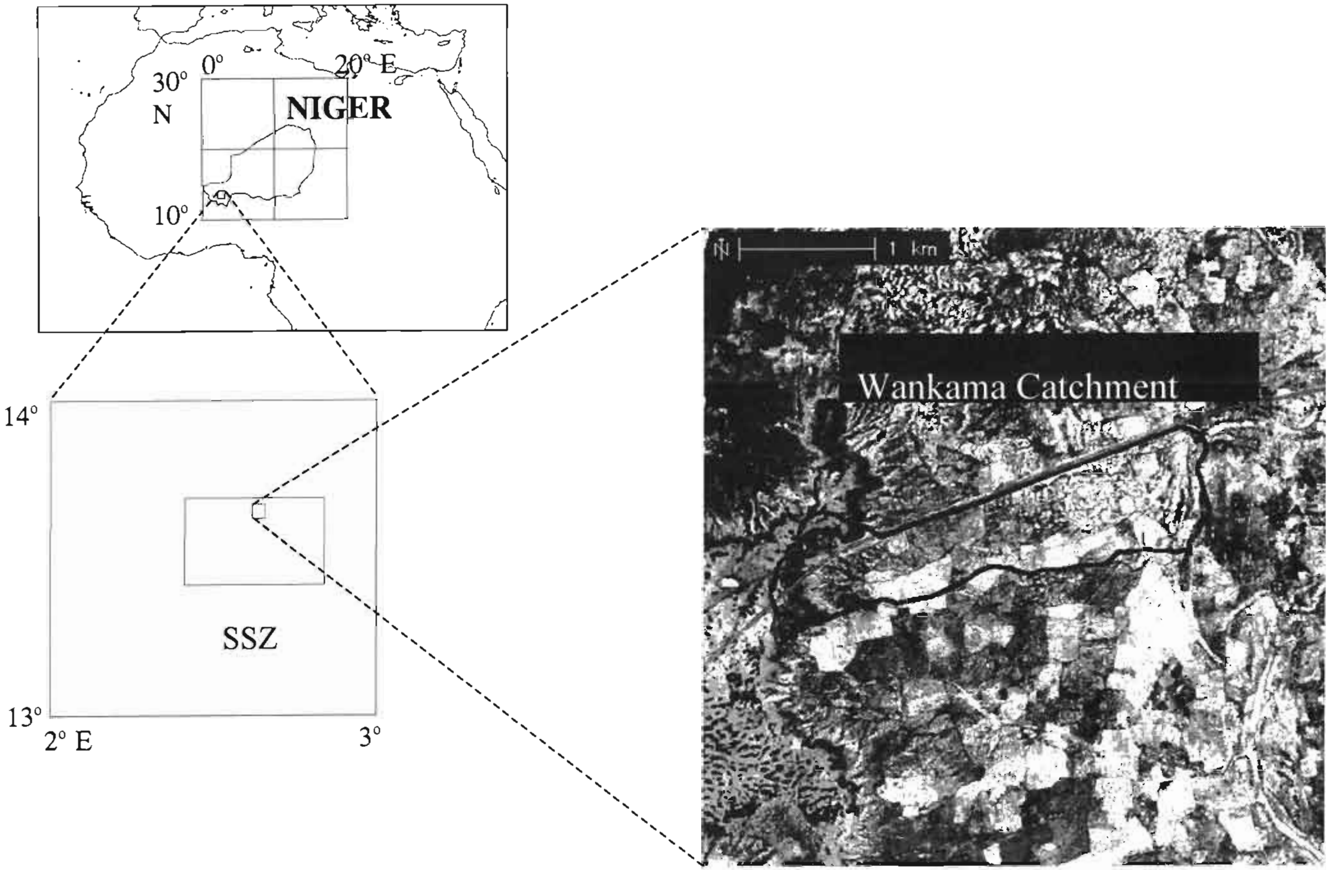

Fig. 1 Location of the Wankama catchment.

grasses and low shrubs. The plateau is covered with sparse vegetation organized in dense bands giving the appearance of a tiger's fur hence the name tiger brush (brousse tigré). Cultural practices affecting runoff production include active and fallow millet fields seen as lighter patches within the catchment boundaries in Fig. 1. Within actively cultivated millet fields, the crust is periodically disturbed to enhance infiltration during the growing season (Peugeot *et al.*, 1997).

Model features

Runoff production and transfer are tightly coupled due to the loss mechanisms present in the Wankama pool. Thus modelling these processes requires a distributed hydrological model capable of representing the processes. The GIS-based distributed model, *r.water.fea* (Vieux & Gaur, 1994) was used for this catchment. Features of this model include finite-element-in-space and finite-difference-in-time solution to the kinematic wave equations. Runoff is produced in each grid cell, depending on the rainfall rate derived from recording raingauges, the infiltration rate estimated using the Green and Ampt infiltration equation, and the incoming surface flow coming from upstream cells. Infiltration rates are based on soil crust classification developed by Casenave & Valentin (1989). As runoff is routed from cell to cell via a finite element network, runoff may infiltrate in both overland and channelized flow areas. This is particularly important in this catchment and regionally where large losses in sand filled ravines are responsible for low runoff coefficients at the catchment-scale usually less than 10% (FAO, 1996). The model response is used to investigate the sensitivity of the hydrological system to drought, in order to gauge the magnitude of the runoff response to reduced rainfall conditions, and to bound the amplification or attenuation effects of the hydrological system under the climate scenarios tested.

Climate scenarios

Climatic change can manifest itself in a variety of ways; hence a variety of mechanisms that reduce rainfall could be imagined. For instance, scenarios of fewer storms; same number but less intense storms; or reduced areal coverage could be supposed. A significantly reduced number of events, particularly during the more intense rainfall months of July and August, has been identified as the predominant cause of the drought experienced in this region (Le Barbé & Lebel, 1997). Hence the principle of event withdrawal from the 1992–1995 monitored period has been used as an exploratory method to investigate the impacts of climate change on the hydrological response of the basin. Rainfall over this period of four rainy seasons consisted basically of 75 events, which served as the basis for this study. A climate scenario consists of a rule for stepwise elimination of events among this set.

The manner in which events are eliminated undoubtedly affects the magnitude or sensitivity of the response. If there are fewer low-intensity storms, then the overall runoff reduction in response to such a scenario might be expected to be less severe than if there were a reduction in the high-intensity storms. One objective here being to set bounds to the relative hydrological response, two extreme scenarios were obtained by removing the events in respectively increasing or decreasing order, when ranked according to their runoff production efficiency measured by the runoff coefficient (volumetric rainfall-to-runoff ratio). Two additional, more reasonable, scenarios were built based on a date criterion instead of a hydrological criterion, for the purpose of comparison.

The four drought scenarios simulated over four rainy seasons, 1992–1995, for the Wankama watershed basin are: (a) storms removed from the first and the last of each year (termed hereafter FLEY); (b) storms removed during the first and last of each July–August period (FLJA); (c) more intense storms removed first (MISF); (d) less intense storms removed first (LISF). In the FLEY scenario, the number of storms is successively decreased by 8, 12, 16, 24, 32, 40 storms out of the 75. In the FLJA scenario, the number of storms is successively decreased by 8, 16, 24, 32, 40, 48 storms out of the 75, whereas in the last scenario this series is taken as high as 60 storms removed to achieve a comparable maximum reduction in total rainfall. In the first two scenarios (FLEY and FLJA), withdrawal is performed according to calendar order, whereas in the last two scenarios (MISF and LISF) the 75 storms are rank ordered in terms of runoff coefficient for event elimination. FLJA may probably be viewed as the most realistic scenario if one refers to the past manifestation of the drought actually experienced in the Sahel.

RESULTS AND DISCUSSION

Hydrological sensitivity to drought

As expected, significant differences in the hydrological response can be seen, depending on the scenario in which the drought manifests itself. We can view the hydrological sensitivity first in terms of global runoff coefficient (ratio of runoff volume measured at the pool to rainfall volumes cumulated over all selected events for each scenario) over the simulation period. Global runoff coefficients for the FLEY and FLJA scenarios stay relatively stable, varying from 8.2% to 10.2% for reductions in number of rainfall events ranging from 8 to 48. Secondly, we can compute the reduction in runoff in response to a reduction in rainfall volume. This gives us an idea as to the linearity of the hydrological response by the catchment to the climatic change.

Rainfall-runoff can be measured as percentages of runoff volume reduction in response to rainfall volume reduction. Depending on the scenario used to simulate the drought, we observe very different responses. Figure 2 shows the relationship between percentage reduction in runoff volume to percentage reduction in rainfall volume for the four scenarios. Most significantly, the extreme MISF scenario produces about 60% less runoff in response to 30% reduction in rainfall or about 2:1. The more realistic FLEY and FLJA scenarios are on the order of 1:1 or about 30% less runoff in response to 30% reduction in rainfall. Storms eliminated during the July–August period (FLJA) produce a greater reduction in rainfall and runoff than those eliminated during the first and last of the rainy seasons (FLEY) showing that this central period of the rainy season is responsible for more runoff production due to larger more intense storms.

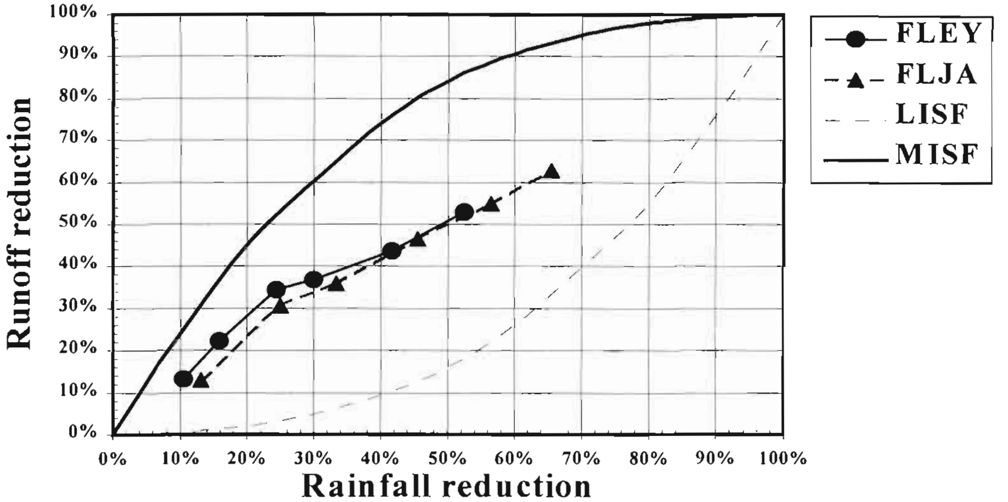

Fig. 2 Runoff volume reduction under scenarios: FLEY, FLJA, MISF, LISF.

CONCLUSIONS

Estimated hydrological response to the drought conditions is presented for a small catchment in the Sahel. The sensitivity is more or less linear with a 1:1 reduction of runoff to rainfall. The more extreme MISF scenario results in a 2:1 reduction in runoff to rainfall volume. It should be noted that the period 1992–1995 is within the period of the Sahelian drought. Further elimination of rainfall events beyond the already droughty conditions reveals the response to an even worse condition than the existing drought condition.

Depending on the storm selection criteria, the impact on runoff relative to rainfall reduction may be as high as 2:1, in the worst scenario of the most intense storms being eliminated. In this realization, a 30% rainfall decrease, which is on the same order as the difference between the periods before and after 1970, would result in a 60% runoff reduction. The more plausible FLJA and FLEY scenarios yield roughly 1:1 responses. Whereas, in terms of global runoff coefficients, the response falls within a narrow range between 8 to 10%.

These results emphasize the variability of the hydrological response to given regional climatic changes and the importance of a detailed characterization of possible rainfall changes at the event scale. Understanding the impacts on water resources due to climatic change depends on coupled processes ranging from the GCM scale of atmospheric circulation to mesoscale processes responsible for the convective storms delivering rainfall at the catchment scale. It is shown that the rainfall distribution scenario has tremendous impacts on the behaviour of the hydrological system emphasizing the need for future research (PRNH) directed towards coupling GCM, mesoscale, and catchment processes to make estimates of hydrological response to climate change.

Acknowledgements Much of the simulations and application of r.water.fea to the HAPEX-Sahel data were conducted with support by the Laboratory of Hydrology, ORSTOM, BP 5045, F-34032 Montpellier, France. The first author greatly acknowledges this support with further appreciation extended to Thierry Lebel, ORSTOM/Groupe PRAO for insights and ideas on characterization of drought and rainfall in the Sahel.

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